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Development of Bias In Analytical Predictions Based on Behavior of Platforms During Hurricanes

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Abstract

Hurricane Andrew was a very intense storm that significantly loaded hundreds of platforms in the Gulf of Mexico in August 1992. This event provided a unique opportunity to study the true behavior of offshore platforms subjected to large hurricanes and improve procedures used in analytical predictions.

A Joint Industry Project (JIP) was initiated by 13 oil companies and the U.S. Minerals Management Service (MMS), wherein a methodology was developed to use information from observed platform conditions resulting from Andrew and the hurricane hindcast data with capacity, reliability, and Bayesian updating analyses to determine a measure of differences (biases) in the analytical predictions and field observations. The procedures used for structural integrity analysis were also improved as a result of this study. Phase I of this project completed in October 1993[1-4] defined a global bias factor. A study of foundation behavior was completed following Phase I and determined bias factors specific to foundation failure modes.[6,7] This paper presents the approach followed in the most recent phase of this project in which bias factors specific to jacket and two foundation failure modes (lateral and axial) were developed. This study utilized an updated storm hindcast, improved analysis models, and a more detailed calibration procedure.[5] The three bias factors were developed and were found to differ significantly.

The bias factors developed through this study have provided means to further improve procedures used in the assessment of existing platforms. The proper use of these new analytical methodologies and bias factors will produce more appropriate and cost-effective mitigation measures for safe platform operations. The methodology for establishing bias factors developed and proven in these projects is applicable to other offshore regions and production systems with specific environmental, geotechnical, material and structural features.

Introduction

In August of 1992 the Gulf States were subjected to one of the most intense hurricanes in recorded history. Hurricane Andrew exhibited peak wind speeds of over 155 miles per hour and created wave heights in excess of 70 feet. The track of Hurricane Andrew led through southern Florida, where most of its destruction occurred, progressed through the Gulf of Mexico and eventually made its final landfall near Morgan City, Louisiana. Andrew caused over 50 deaths onshore and extensive property damage. Andrew represents one of the costliest natural disasters in US history

The hurricane path includes a region of the Gulf that is very densely populated with offshore platforms. As shown in the Fig. 1, the center of the hurricane traversed the Mississippi Canyon, South Timbalier, Ship Shoal and Eugene Island areas. Along its path through the platform areas, Andrew's waves typically exceeded the 100 year return period criteria used for the design of new structures. The region of platforms most significantly loaded by Andrew, as defined by the U.S. Minerals Management Service (MMS), included approximately 700 platforms located in the Eugene Island, Grand Isle, Mississippi Canyon, Ship Shoal, South Marsh, South Pelto, South Timbalier, and West Delta areas. Many of these platforms were older structures that were not designed to withstand the forces created by a hurricane of Andrew's magnitude. However, inspections following the hurricane revealed that most of the platforms affected by Andrew were not significantly damaged. The vast majority of the damage reported was minor and included items such as bent handrails, damaged walkways, and damaged boat landings. A number of structures experienced significant local structural damage both above and underwater. In some of these instances, the damage was considered to be of significant consequence possibly jeopardizing the overall structural integrity of the platform. In these cases, the damage was either repaired or shown not to degrade global strength to below minimum safety limits.

There were 28 jacket type platforms that suffered substantial damage resulting either in total collapse or rendering the structure unserviceable and beyond repair. In addition, 47 caissons were also significantly damaged or collapsed.[1]

The number of platforms damaged by Hurricane Andrew was significant, however, the event has provided a positive demonstration of the emergency systems in place within the Gulf. This is evidenced by the fact that, because platforms were shut-down and evacuated prior to the hurricane, no lives were lost offshore and less than 2,500 barrels of oil (including 2,000 barrels spilled from a pipeline) were spilled.[2]

Although destructive to the oil industry, the Andrew experience has provided very valuable data that can be used to further understand the performance of offshore structures subjected to large hurricanes. The information gained through the review of platforms that survived, were damaged, or failed during the hurricane can be used to improve procedures for designing new platforms as well as procedures for assessing the integrity of existing structures. Andrew thus provided a unique opportunity to study offshore structures tested under "real-life" full scale conditions.

Previous Andrew and Related Studies

Over the last 3 years PMB and other organizations have completed a number of studies that have related to Andrew and the development of current API guidelines for platform assessment.[3] Some of these studies that have had a direct impact on this work are listed as follows

- Effects of Hurricane Andrew on offshore platforms - Phase I[14]
- Effect of Hurricane Andrew on platform foundations[6,7]
- Investigation of detailed inspections of structures damaged during Andrew[8,9]
- Study of caisson behavior during Andrew[10]
- Assessment of ultimate capacity analysis procedures included in the API guidelines[11,12,13]
- Andrew hindcasts[14,15]
- Strength and stiffness of tubular joints[16]
- Ultimate lateral capacity of piles in clay[17]

In particular the Andrew Phase I and Foundation studies have guided the scope for the Phase II work discussed in this paper. The details of the Phase I work are provided in OTC 7473[4] and of the API/MMS foundation study are presented in a companion paper, OTC 8078[7]. The results and conclusions of the Phase II study represent the product of an extensive 3 year effort.

General Approach

There are various ways in which analytical predictions can be calibrated to match observed behavior more accurately. Each of the individual formulations that enters into the analysis (e.g., calculation of wave load, member strength or soil strength) could be adjusted independently to improve the overall prediction. This method would be preferable if data were available to support such adjustments. Unfortunately, while we do know in some instances that platforms have survived unexpectedly (i.e., they were predicted to fail but survived), we do not know if this is due to an overestimation of loads or an underestimation of strength. Therefore, the calibration procedure that was used did not adjust individual parameters but instead assessed the bias ("*B*") in the safety factor (resistance to load ratio) for each of the three modes of failure. This bias factor was applied in the following form:

$$(R/S)_{true} = B(R/S)_{computed} \quad (1)$$

where R represents resistance or strength and S represents loading. The ratio $(R/S)_{computed}$ is obtained from the state-of-the-practice procedures and guidelines for ultimate capacity and wave loading analysis. In this form, a value of *B* greater that 1 indicates conservatism in the procedures used while values of *B* less than 1 indicate unconservative methods. The objective is to infer the value of B from the information available from field observations. This information is not typically definitive and B must therefore be defined in the form of a probability distribution.

Fig. 2 presents an overview of the integrated methodology followed to combine various sources of information from several platforms and analyses to estimate the bias factors. The steps include. 1) capacity analysis, 2) reliability analysis, 3) Bayesian updating. In this Phase, three bias factors specific to different failure modes with different uncertainties were developed. a jacket bias factor (B_j), a lateral foundation bias factor (B_{fl}), and an axial foundation bias factor (B_{fa})

Platforms Investigated

Thirteen jacket platforms were studied during Phase I. Nine steel jacket platforms and three caissons were investigated in this Phase. A summary of the platforms selected for calibration is given in **Table 1.** The location of these platforms with respect to the eye of Hurricane Andrew is shown in **Fig. 1.** These platforms were selected from the population of heavily loaded structures on the basis of the availability of good data (e.g., drawings, pre- and post-storm inspection reports, soil data) and the estimated effect on the calibration (i.e., platforms that were damaged or thought to exhibit unexpected behavior were preferred).

There were no jacket type platforms available that were believed to have experienced a foundation failure; however, there were several caissons that experienced full or partial foundation failure. Three of the caissons that were damaged during Andrew and were included in the API/MMS Foundation study[6,7] were used in this Phase II study to estimate better the variation in the foundation lateral capacity bias factor.

The following types of damage were observed in the jacket part of the platforms investigated in Phase II study

- Crushing (ovalization) of chord and cracks in X-braces
- Complete tearing of K-joints at gap in chord
- Bulging of chord and cracks in KT joints
- Buckling of diagonal braces

- Yielding of leg sections
- Complete collapse of platforms (rubbled, failure mode unknown)
- Damage of secondary braces (e.g., flooding)
- Leaning of caissons

Capacity Analysis

Structural capacity analysis was performed to estimate the true response of a platform when subjected to the hurricane hindcast conditions. This analysis is quite different from that used for the design of new structures All aspects of loading and response are modeled based on expected behavior (e.g., mean formulations of component strength are used instead of the lower bound values typically used for design) without factors of safety. Individual components are allowed to yield and fail and are monitored following failure to assess the impact of their failure on the overall response of the structure. An example of such an analysis is illustrated in Fig. 3. All of these analyses were performed using CAP[18] (Capacity Analysis Program) software.

Such analysis is typically referred to as "static pushover" and requires detailed modeling of nonlinear material and geometric behavior. This analysis provides very useful data that cannot be produced through conventional elastic (design) analysis. It involves defining a representative profile of lateral forces (wind, wave, and current) acting on the platform (including any wave forces acting on the deck) and then applying this profile with incrementally increasing amplification factors until the platform's capacity is defined. The ultimate capacity of the platform can then be used to estimate the wave height that would induce platform collapse or it can be compared with the loads due to any reference level loading (e.g., the 100-year return period wave) to determine platform's reserve strength ratio (RSR). The procedures used for this analysis follow the general guidelines provided in the draft API document on assessment of existing platforms.[3]

The results of these analyses were used in the calibration study to determine bias factors specifically for the jacket, lateral foundation and axial foundation components. The definition of component specific bias factors made it necessary to establish the platform capacities associated with failure mechanisms developed in each of these three areas. A total of four analyses were therefore performed for each steel jacket platform to obtain uncoupled estimates of platform capacity for specific failure modes. The Base Case analysis was performed to establish the expected mode of failure based on the current best estimate of the physical properties and local response characteristics of all components of the structure. All components (jacket elements, piles and supporting soils) that could potentially contribute to a failure mechanism of the platform were represented to capture their elastic and inelastic response. The other three analyses were performed to estimate the ultimate capacities of the platform associated with the jacket structure failure mode (local failure and inelasticity in the braces, joints, horizontals, and legs), the lateral foundation mode (pile yielding/hinging mechanism), and the axial foundation mode (pile pullout/plunging) In each of these cases the other two categories of failure modes (e.g., jacket, axial pile failure modes) were suppressed by increasing the strength of appropriate components. These analyses therefore isolated the effects of uncertainties associated with the modeling of strengths and post-yield behavior of other failure modes and defined uncoupled estimates of the ultimate capacity of the platforms as controlled by each of the different failure modes independently

A fully coupled nonlinear jacket-pile-soil model was developed for each platform. Several modeling enhancements were made to improve the analytical predictions including:

- Explicit joint modeling
- Modeling of conductors
- Variable pushover load pattern

The procedures followed to model the soil shear strength, lateral and axial soil capacities are discussed in detail in a companion paper OTC 8078[7]. Some additional analysis procedures ("recipe") used were discussed in an earlier paper OTC 7473.[4] Improvements were made on the loading side by using variable pushover load patterns for cases where deck inundation occurred. This was found to provide a more accurate estimate of overturning moment.

Calibration

The objective of the calibration is to establish a distribution on "B" (Eq. 1) that is consistent with the observed behavior. The updating is based on the Bayes theorem of probability[19] which is described in general terms by the following expression

$$\textit{Posterior distribution} \propto (\textit{Prior distribution}) \times (\textit{Likelihood function}) \quad \text{..........(2)}$$

or for a single bias factor, it can be stated as

$$f''_B(b) \propto f'_B(b) \quad lk\left(b \mid new\ information\right) \quad \text{.......(3)}$$

in which $f'_B(b)$ is the "prior" distribution on the bias factor, $f''_B(b)$ is its "posterior" distribution, and lk(b | new information) is the "likelihood function" which reflects the information about b obtained through the observations.

In case of multiple bias factors, the joint posterior distribution of the bias factors would become:

$$f''_{B_j,B_{fl},B_{fa}}\left(b_j,b_{fl},b_{fa}\right) \propto f'_{B_j,B_{fl},B_{fa}}\left(b_j,b_{fl},b_{fa}\right)\ lk\left(b_j,b_{fl},b_{fa} \mid new\ \ information\right) \quad \text{..........(4)}$$

where the joint prior distribution is assumed here to be the product of marginal priors:

$$f'_{B_j,B_{fl},B_{fa}} = f'_{B_j} \quad f'_{B_{fl}} \quad f'_{B_{fa}} \quad \text{...... (5)}$$

The marginal posterior distributions, mean values and COVs, of the three bias factors are determined by numerical integration from this joint distribution The change in the mean values of the bias factors from the prior to the posterior distribution provides a measure of information provided by Andrew on the bias (conservatism or non-conservatism) in the ratios of capacity to load predictions for each failure mode

In most cases the joint posterior distribution will not simply be the product of marginal posteriors (i e., the 3 Bs are not independent a "posteriori") The bias factors are interdependent, for example, due to the fact that a failure observed in the jacket implies that axial foundation capacity is larger than the jacket capacity

The Bayesian analysis method was applied previously to offshore structures during the cooperative project on offshore platform reliability organized by Amoco.[20,21] Bayesian applications are also presented in the API PRAC Project 89-22 Report[22] and in other offshore literature.[23,24]

Calibration Steps. The calibration task involved determination of distributions of bias factors as follows

- The assumed, or "prior," definitions of (B_j and B_a), were defined by a normal distribution with a mean value of 1 (i e., there was no initial reason to expect bias in the procedures) and a coefficient of variation (COV) of 30% The axial foundation bias factor (B_a) was given a prior mean of 1 3 based on previous API PRAC work.[6]
- Probabilities of occurrence (e.g., failure) were determined based on the capacity analysis results and hindcast data.
- Joint likelihood functions were developed for each platform to define the probabilities of occurrence of the observed behavior given specified values of bias factors
- The updated joint distributions of the bias factors were calculated using the prior distributions and the joint likelihood function for each platform.
- The cumulative joint distribution of bias factors was determined using the product of their assumed prior distributions and all the individual platform likelihood functions.

The process is illustrated for a single bias factor in Fig. 4 The shift in the bias factor distributions is a function of the degree of unexpectedness of the observed results For example, if a platform was unquestionably expected to fail during the storm, it would be assigned a relatively high failure probability. If this platform was observed to survive, the likelihood function describing the probability of survival would exhibit a significant shift to higher values of *B* This would then result in a significant shift of the bias factor distribution to larger values of *B* (i e., this case would suggest that the analysis was very conservative)

Unexpected failures shift the distribution to lower values of *B* (to the left). Unexpected survivals shift the distribution to higher values of *B* Expected failures and survivals have a much less effect on *B* Damaged cases provide very useful information since they describe much more specific observation data than either survivals or failures All that is known with a failure is that the load exceeded capacity It is not known to what degree the capacity was exceeded. Similarly, survivals show that capacity exceeded load but by an unknown amount. Damaged cases describe a specific physical response to specific loading and tend to improve the definition of the bias factor by reducing the uncertainty

This process was performed considering three bias factors and included the development of joint likelihood functions to include the effect of coupling between the failure modes

Use of Observations to Develop Likelihood Functions

The information about the degree of design conservatism that is contained in a statement such as "Platform X survived hurricane Andrew" may be very complex Likelihood functions serve to quantify that information unambiguously

The value of B (a bias) is inferred indirectly from structural performance under hurricane loads. The objective is to interpret the observed behavior of the structure in terms of the implied relative likelihood's of the different values that B might be Simple, one-dimensional, examples of likelihood functions are presented first.

Deterministic Likelihood Functions. For clarity the development of likelihood functions is presented for three simple cases in which it is assumed that the estimates of maximum base shear (S) and capacity (R) are known with certainty

Survival Case. Consider first the case in which the guideline capacity (R) of the structure is known to be precisely 1,000 units and the maximum base shear (as calculated by the guideline) that the structure experienced during the event was precisely 1,100 units. Despite the fact that load exceeded capacity, the structure was observed to have survived. It is clear that the guideline procedures must have a bias of at least 1.1 but there is no evidence other than this. Based on this result alone, all possible values of b less than 1.1 have zero likelihood and all values above 1.1 are equally likely. A plot of the likelihood function for this case is shown in Fig. 5a. The value of $lk(b \mid survival)$ for values of b greater than 1.1 is arbitrary, the available information is only that the *relative* likelihood's are equal. The important information in this particular outcome is that the guidelines cannot be unconservative

Failure Case. Under the same circumstances of precise knowledge of guideline R and S, if an observation of collapse were observed when R is 1,000 and S is 1,250, then the likelihood function on B would be zero for values of b greater than 1.25 and some arbitrary constant value for all values of b less than 1 25 (Fig 5b) In contrast to the first case which indicated that there is some degree of conservatism in the guidelines, this failure case was not a "surprise" given the guideline values of R and S. The likelihood function in the observed failure case reflects this by yielding no new information about the value of B other than simply excluding any potential extreme conservatism beyond an upper possible limit of 1.25. In particular, by itself, this "expected" outcome cannot exclude the possibility that the guidelines are unconservative.

Damage Case. Finally consider an observation of partial damage, (e.g., a single buckled brace). This outcome implies that the load exceeded some threshold of damage but was insufficient to cause further distress. This case is included by returning to the results of the pushover analysis to obtain the base shears at which these thresholds were predicted to occur. If first brace failure was predicted at 75% of the collapse capacity, R, and no further major distress was predicted until 95% of R the outcome implies that the load S must have been larger than 0.75 bR and less than 0.95 bR. This implies a bias in the range of (S/0.95R) and (S/0.75R). If the ratio S/R was known with precision to be 1.0, then this damage observation would place the value of b between 1.05 and 1.33 (Fig. 5c).

Such damage cases are extremely valuable in that they tend to bound the value of b from both below and above unlike the simple failure or survival case. This also suggests that the "survival" (or more precisely "did not collapse") case above may deserve to be looked at more carefully. The information may be more complete (e.g., the structure was also "undamaged"). In that case inspection of the pushover analysis might reveal that the outcome could be interpreted better as b is greater than R/S times a factor, that is determined based on the load level at which first observable damage could be expected. This clearly implies still more guideline conservatism than the simple "survival" interpretation of the outcome.

Probabilistic Likelihood Functions. In the more realistic case there is a lack of information about the precise conditions of the structure and loading that results in uncertainty or ambiguity in the interpretation of the outcome. The likelihood function is still interpreted as the likelihood of B given the outcome but it is defined now as the probability of that outcome given the value of B, or

$$lk(b\,|\,the\ outcome) = P[the\ outcome\,|\,b] \quad\text{......................(6)}$$

Survival Case. Repeating the simple survival case, the likelihood of any particular value of B given that outcome is now calculated as the probability that bR/S is greater than unity (i.e., survival) given that particular value b. The probability analysis must assess what is actually known about R and S. For example, the actual maximum wave height, which enters in the calculation of S, is uncertain. Similar uncertainties effect the base shear and capacity of the structure. In the survival example above, the base shear could be defined now with a median value of 1,100 units *and* a coefficient of variation (COV) of 40% and the ultimate capacity could be defined with a median of 1,000 units with COV 15%. Then, because of this uncertainty about R and S, there is also additional implied ambiguity about the value of B. The step function in Fig. 5a will be replaced by an S-shaped curve "centered" on 1.1 and approaching zero only for very small values and a constant (one) only for very large values.

To calculate the likelihood value for any specific value of B, say b is 0.75, one calculates the conditional survival probability, P[bR/S > 1 | b], or in this specific case P[0.75 R/S > 1], i.e., P[R/S > 1.33]. In contrast, for b equal 1.33, the likelihood is P[R/S > 0.75]. This second number is clearly larger than the first because the ratio R/S is a random variable with median about 1.1 and COV about 45%. The shape of a survival likelihood function was shown in Fig. 4b.

Failure and Damage Cases. The likelihood functions in the more realistic versions of the other two cases discussed previously are simply smoothed versions of the sharp functions given in Fig. 5b and 5c. The relative likelihood of any particular value b in the case of an observed failure is simply the probability of failure, P[bR/S < 1 | b], conditional on that value of B being its true value, (i.e., P[R/S < 1/b]), which is only a slightly modified version of the usual probability of failure statement P[R/S < 1], hence it can be calculated and plotted versus b. Similarly, in the above damage case, the likelihood function is P[(1/0.95)/b < R/S < (1/0.75)/b], which can be evaluated for various values of B.

Multiple Platforms. If the outcome consists of the observation of the behavior of more than one structure, then the likelihood function of B given this suite of observed behaviors is used. If the observations are probabilistically independent, (e.g., the random variables representing the information available about each of the platform loads and capacities are mutually independent), then the likelihood function associated with the outcome involving "n" structures is simply the product of the individual likelihood functions. So, for example, given the two (one survival and one failure) observations associated with Figures 5a and 5b, the likelihood function would be a constant between b of 1.1 and 1.25 and zero elsewhere. If the outcome included all three of the simple cases (associated with Figures 5a through 5c), then the likelihood function would remain the rectangle just described because the damage case now brings no new information. On the other hand, in the more realistic cases, the combination of the individual likelihood functions would produce smoothed versions of this rectangle and the damaged case would tend to reduce uncertainty in B.

Thus, the combined likelihood function of *B* given the observed behavior of a number of platforms, with a combination of survivals, damages, and failures would be:

$$lk(b\,|\,n-observations) = \prod_{\substack{platform\\ i}}^{n} [lk_i(b\,|\,observation)] \quad\text{......(7)}$$

where "n" is the total number of platforms.

Joint Likelihood Functions. Joint likelihood functions are introduced to define multiple bias factors associated with different modes of behavior. The observations are interpreted to assess the relative likelihoods of different values of these factors

Survival Case Assuming that the load and capacity of two failure modes (e g, jacket R_1 and foundation R_2) are known precisely, then an outcome such as "the structure survived" implies that both B_1R_1/S and B_2R_2/S were greater than unity, where B_1 and B_2 are two bias factors Repeating the specific deterministic examples ($R_1/S = 1.1$ and $R_2/S = 0.8$), the joint likelihood function on B_1 and B_2 becomes

$$lk(b_1, b_2 \mid \text{the outcome}) = c \text{ for } b_1 > S/R_1 (= 0.9) \text{ and } b_2 > S/R_2 (= 1.25)$$
$$= 0 \text{ elsewhere} \qquad (8)$$

in which c is some arbitrary constant. This function describes a rectilinear box of height c sitting on top of the cross-hatched region in Fig 6a. Elsewhere in the positive quadrant the function is zero, (i e., these are impossible combinations of values of B_1 and B_2).

Failure Case. Consider the same set of values as above but assume now the outcome has been interpreted instead as collapse due to unknown cause. One or the other (or possibly both) of the modes had inadequate capacity. The joint likelihood function in this case is just the "reverse" of that just described (i e, it is zero where $b_1 > 0.9$ and $b_2 > 1.25$ and it equals a constant c as shown in Fig 6b).

The information about B_1 and B_2 have become coupled. In describing what is known about B_1 from this outcome the other potential mode of failure must be addressed as it may have been "the cause" of failure A likelihood function cannot be described for B_1 or B_2 separately and their joint likelihood function is, therefore, not a product of two separate functions. This is possible in the survival case because survival indicates survival of *both* modes, not just one or the other.

Multiple Conditions. In cases where failure or damage is attributed to a specific mode the problem is formulated differently. A case where the jacket failed and the foundation survived would imply that $b_1R_1/S < 1$ and that $b_2R_2/S > b_1R_1/S$. This would not necessarily imply that $b_2R_2/S > 1$ because the load on the foundation was limited by the failure of the jacket. It is known from this outcome that $b_1 < 0.9$ and $b_2 > b_1$ for the same specific numerical assumptions. The joint likelihood function for this case is constant over the cross-hatched region pictured in Fig. 6c. Again in this case the information about the bias factors is coupled.

For more realistic probabilistic cases, the formal calculation of the joint likelihood of two specific values of B_1 and B_2 requires calculation of the conditional probability of a joint event such as (in the survival case above) $b_1 R_1/S > 1$ and $b_2 R_2/S > 1$ given the values of B_1 and B_2. This calculation is substantially more complicated than that of the previous probabilistic single bias cases because it involves not only a joint event but sub-events which include common random variables (S) and possibly correlated random variables (R_1) and (R_2), both of these conditions induce probabilistic dependence between the two sub-events This kind of dependence implies a further coupling between the inferences that can be made about B_1 and B_2 The plot of representative joint likelihood function for such a case is shown in Fig 8 The other cases, (e g, failure, failure of one mode only, damage) can be similarly formulated. For example the case above that involves jacket failure and foundation survival becomes

$$lk(b_1, b_2 \mid \textit{failure of mode-1 and survival of mode-2})$$
$$= P[(b_1R_1/S < 1) \cap (b_2R_2/S > b_1R_1/S)]$$
$$= P[(R_1/S < 1/b_1) \cap (R_2/R_1 > b_1/b_2)] \qquad (9)$$

in which the b's are specified values and the R's and S are random variables. Complex coupling of the inferences about B_1 and B_2 and potentially difficult computation are indicated

Extensions to Eq 9 were made to develop the likelihood functions for three bias factors and multiple storm hours, and were used in this study

Multiple Platforms. The combined joint likelihood function for three bias case, given the observed behavior of a number of platforms with a combination of survivals, damages, and failures, is obtained by direct multiplication of the individual joint likelihood functions as follows

$$lk\left(b_j, b_{fl}, b_{fa} \mid n - \textit{observations}\right)$$
$$= \prod_{\textit{platform } i}^{n} \left[lk_i\left(b_j, b_{fl}, b_{fa} \mid \textit{observation} - i\right)\right] \qquad (10)$$

Probabilities of Occurrence

The probabilities of occurrence (failure, survival, or damage) were determined for the following calibration conditions

Survival	No damage or only minor, non-structural, damage identified
Type I Damage Case	Known damage to the jacket and foundation assumed to be intact.
Type II Damage Case	Damage exists but is not specifically identified or attributed to the jacket or foundation
Type I Failure Case	Known failure of the jacket and foundation assumed to be intact.
Type II Failure Case	Failure occurred but is not specifically attributed to the jacket or foundation

Load levels defined from the capacity analysis corresponding to the various levels of observed performance (e.g., extent of damage, lack of damage) were selected to define the calibration conditions.

Formulation of Probability of Occurrence. The first and second order reliability methods (FORM/SORM)[19,27,28] were used to determine the likelihood functions, which represent the probability of occurrence (P_o) for various values of B, for the multiple calibration conditions listed above, and a case shown in Eq 9. The conditional probability of occurrence of an outcome, $P_o(B)$ is given in the following form

$$P_o(B) = \int P_o(\mathbf{x}, b) f_X(x) dx \quad \ldots \ldots \ldots \quad (11)$$

where,

$$P_o(x; b) = P\left[\bigcup_i \bigcap \{g_i(\mathrm{Y}, \mathrm{X}; b) < 0\} \middle| X = x\right] \ldots\ldots (12)$$

where $[\bigcup \bigcap g_i(\mathrm{Y}, \mathrm{X}; \mathrm{b}) < 0]$ implies that we are calculating the probability of occurrence of a system of components in this inner loop For example for a survival case where a platform survived all three failure modes, the limit state functions (g-functions) for a three component system would be g_1 as $-(R_1/S-1/b_1)$, g_2 as $-(R_2/S-1/b_2)$, and g_3 as $-(R_3/S-1/b_3)$; and the system relationship would be a simple intersection of three components Further, the extensions mentioned for multiple storm hours would require additional combinations

The "nested FORM/SORM"[25] analysis was used to compute the probability of occurrence of an outcome. The probability of occurrence during a single wave was determined in the inner loop analysis The probability of occurrence of a single event (probability of survival during a seastate) was determined in the outer loop analysis, by introducing an auxiliary random variable per Wen and Chen [25]

In this application the outer loop random variables denoted by X, included significant wave height (H_s), current (V_c), estimated capacity (R); and the inner loop variable vector, Y, included individual wave height ($H|H_s$) and error in base shear estimate (ε_o) The error in base shear represented the wave-to-wave variabilities within a seastate. See OTC 7473[4] and OTC 8078[7] for further definition of these variables and their distribution used in these studies

The integration over all possible outcomes of conditions of random variables in vector X provided the probability of failure for given values of B

The probabilities of occurrence of specific calibration conditions were determined in this study using RELACS[26] software, which includes nested FORM/SORM and system reliability analyses The probabilities of occurrence for specific calibration conditions were determined for a large number of combinations of the three bias factors. The probabilities of occurrence for the different combinations of b_j, b_a, and b_a define the joint likelihood function for each observed behavior.

Example Application

The methodology is demonstrated through an example application on an 8-leg platform that experienced no damage during post-hurricane field inspections. The hindcast estimated a maximum wave height of 59 feet for this location which resulted in guideline estimated maximum metocean loading of 3,700 kips.

The analysis (Base Case) estimated an ultimate capacity of 3,800 kips which was limited by the development of a mechanism in the base of the jacket. The load-displacement results for this analysis are provided in Fig 7. The analysis predicted that the K and KT joints in the lower two bays of the structure would fail at approximately 3,000 kips of lateral load followed immediately by yielding of horizontals. Pile pullout was predicted at 3,450 kips and fully plastic pile sections between 3,570 and 3,700 kips This analysis predicted that significant damage should have occurred for load levels below that corresponding to the maximum wave height. The inspections of this platform revealed no damage of the elements that were predicted to fail.

The capacity analysis results for the cases with failures limited to the jacket, to the foundation yielding/hinging, and to the foundation axial (overturning) failure modes are also presented in Fig 7. These results indicate that the jacket capacity is the same as the Base Case and that the foundation lateral capacity and foundation axial capacity are 16% and 5% higher than the Base Case estimate, respectively. Therefore the lowest capacity estimate in this case is governed by the jacket. But given the uncertainties this conclusion cannot be definite.

This case was interpreted as a no damage case and the calibration was performed under the assumption that the first event in the jacket (joint failure), and fully plastic sections in several piles, and pullout of several piles were not observed. The joint likelihood function for B_j and B_a is shown in Fig 8 and their marginal likelihood functions are shown in Figs 9 and 10. The joint posterior distributions for two pairs of bias factors are given in Figs 11 and 12. The marginal posterior distributions derived for three bias factors are shown in Figs 13 to 15; they indicate that, for this individual platform, the shift in mean is 30% for jacket bias, 15% for foundation lateral bias, and 8% for foundation axial bias.

The range of likelihood functions and bias factors determined for the full sample of platforms included in the study was significant and the values shown above in no way indicate the final bias factors These numbers are shown solely to demonstrate how the methodology works and should not be applied to other platforms

Conclusions of the Study

1. The primary conclusion of the Phase II study was a confirmation of the previous expectation that the foundation bias factors were significantly greater than that for the jacket, indicating significant additional conservatism in foundation design. The bias factors show that formulation of jacket capacity is moderately conservative.

2. The variation in component bias factors and coupling between individual modes indicates the need to determine "failure mode specific" capacity estimates which isolate the impact of uncertainties associated with the modeling of the elements defining the individual mechanisms. An improved understanding of platform behavior is developed through failure mode specific analyses which can help in development of more appropriate and cost effective mitigation plans. In some cases, mitigation measures based on minimal analysis could be counter productive or too costly.

3. The improved structural modeling procedures utilized in this study have provided predictions that are very representative of true platform behavior. Improvement in specific component response (e.g., K joints with $\beta = 1$) will further improve the ability to match local behavior.

4. The definition of bias factors can be further improved as additional platforms subjected to hurricanes are included in the calibration. In particular, structures that have experienced significant loading provide very useful information to support the calibration. This improvement can come both in the form of refinement to the current bias factors and development of bias factors that can be used more directly within the analysis. This could include, for example, bias factors specifically for joints, braces, and piles.

5. These bias factors have provided a better appreciation of the uncertainties and biases that affect reliability analysis. The API and the regulatory bodies can use the results in the development of guidelines and criteria for platform assessment.

Acknowledgments

We are grateful to the JIP participants who have provided technical guidance and funding to complete the Phase II work. The companies that provided funding were Amoco, Chevron, Exxon, MMS, Mobil, Phillips, Shell, and UNOCAL. In addition, we are thankful to Prof. Fred Moses, Risk Engineering Inc., MSL Engineering (UK), Oceanweather Inc., and Trunkline for providing information needed for this project.

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Table 1 – Salient characteristics of platforms used in calibration

Calibration Case	Platform	Water Depth (ft.)	Year Installed	Number of legs/piles	Performance During Hurricane Andrew
Survival	A	170	1964	4	No damage
	B	137	1963	8	No damage to primary elements
	C	223	1965	8	No damage
Damage	D	137	1962	8+2 tripods	Diagonal braces buckled
	E	142	1965	8	Major damage to K and X joints
	F	62	1969	4	Major damage to K-joints
	G (#1)	35	1984	1	Leaned 12 degree
	H (#1)	53	1983	1	Leaned 15 degree
	I (#1)	50	1983	1	Leaned 30 degree
Failure	J	137	1964	8	Platform rubbled
	K	180	1958	8	Collapsed due to jacket legs and piles yielding
	L	61	1969	4	Platform collapsed

#1 indicates caisson platform

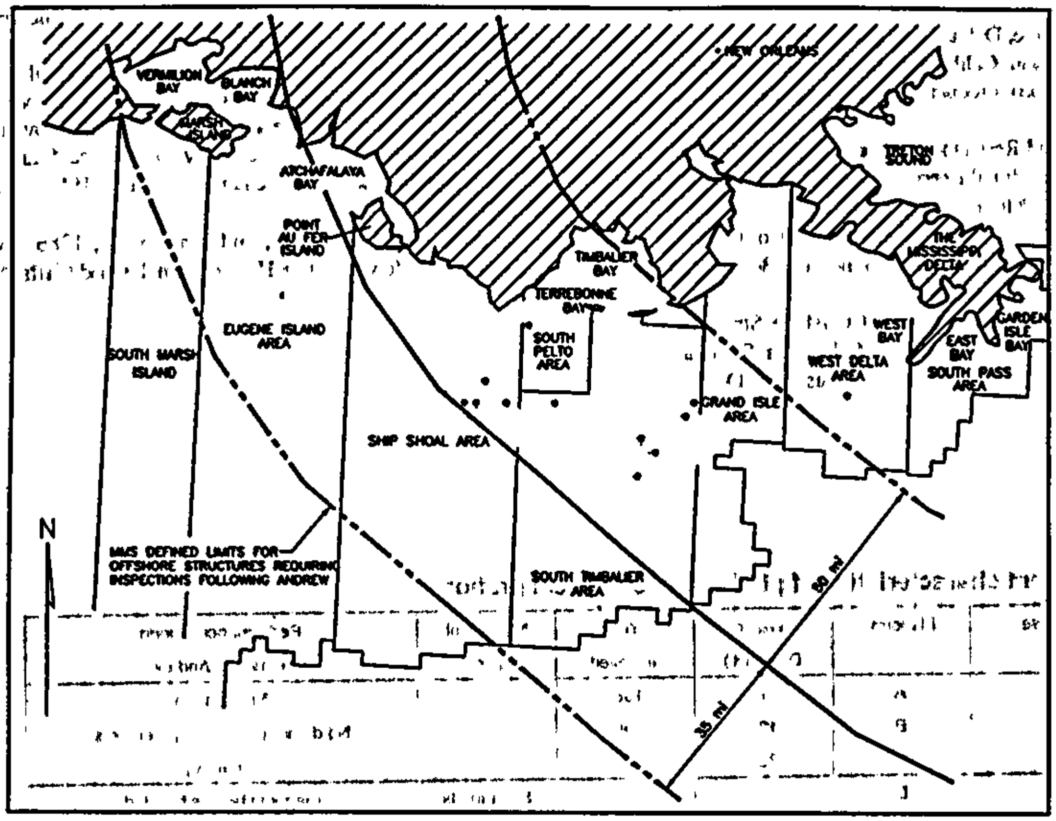
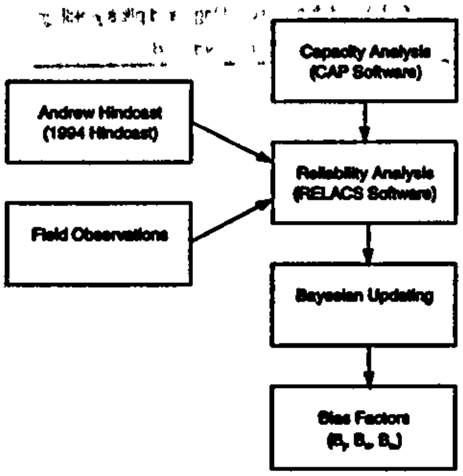


Fig. 1–Path of Hurricane Andrew with platforms used in calibration



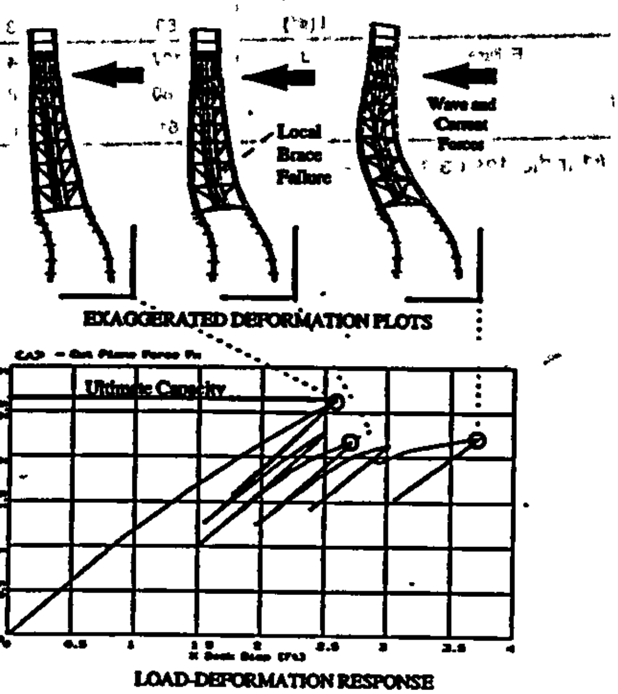
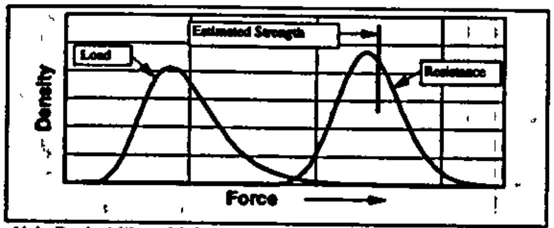
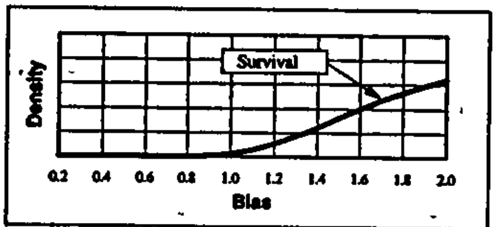


Fig. 2– Calibration Methodology

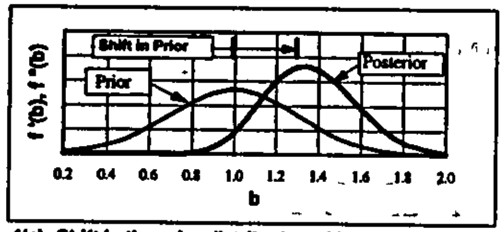
Fig. 3–An example of capacity analysis



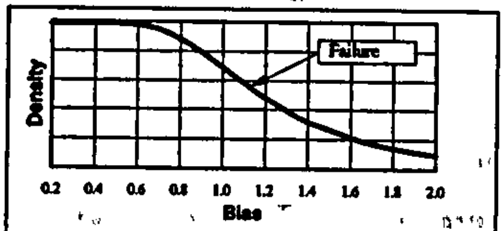
4(a)–Probability of failure, P_f



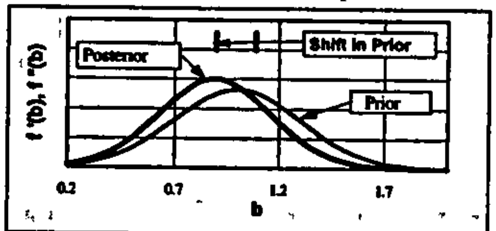
4(b)–Likelihood function for an unexpected survival



4(c)–Shift in the prior distribution of bias factor due to calibration of an unexpected survival case

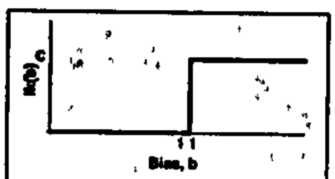


4(d)–Likelihood function for an expected failure case

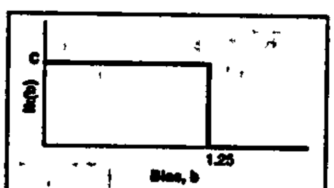


4(e)–Shift in the prior distribution of bias factor due to calibration of an expected failure platform

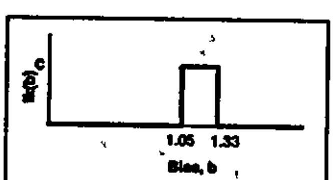
Fig. 4–Development of distribution of a bias factor
(These illustrations are to demonstrate the process and are not applicable to any specific platform.)



5(a)–Survival case

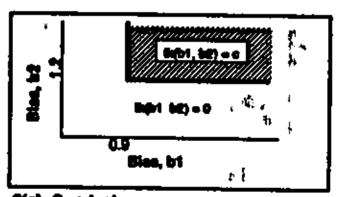


5(b)–Failure case

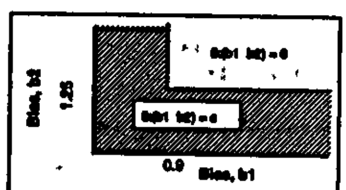


5(c)–Damage case

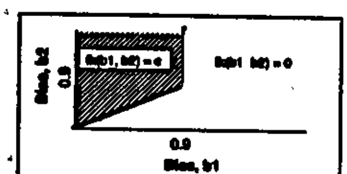
Fig. 5–Simple (deterministic) likelihood functions



6(a)–Survival case



6(b)–Failure case (mode unknown)



6(c)–Failure in mode 1, mode 2 survived

Fig. 6–Simple (deterministic) joint likelihood functions

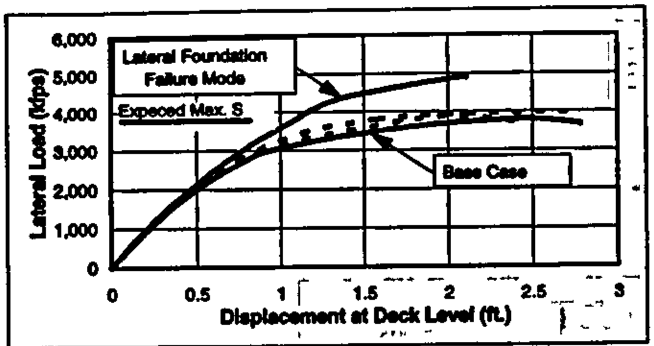


Fig. 7–Comparison of load-displacement behavior and capacity for failure mode specific capacity analyses

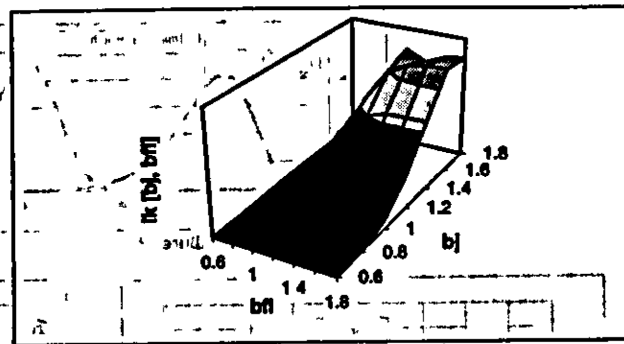


Fig 8–Joint likelihood function for B_j and B_f for an example platform undamaged during Andrew

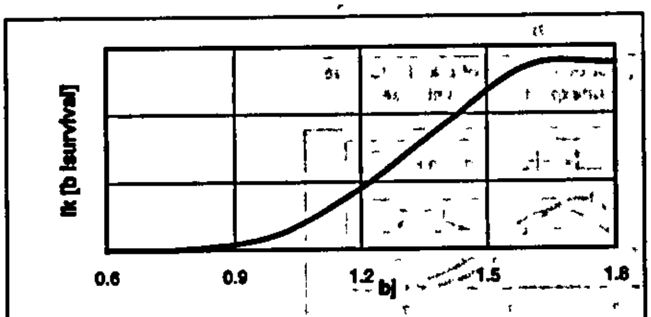


Fig. 9–Likelihood function (marginal) for bias, B_p derived from joint likelihood function in Fig. 8

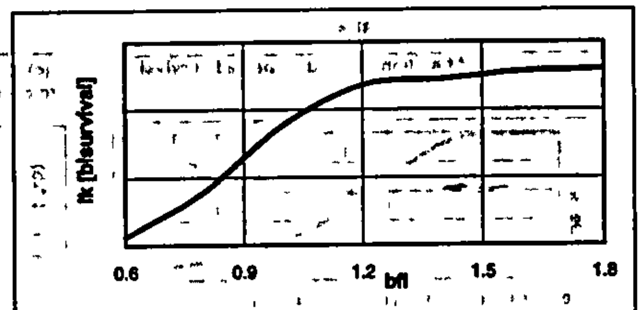


Fig 10–Likelihood function (marginal) for bias, B_{fl} derived from joint likelihood function in Fig 8

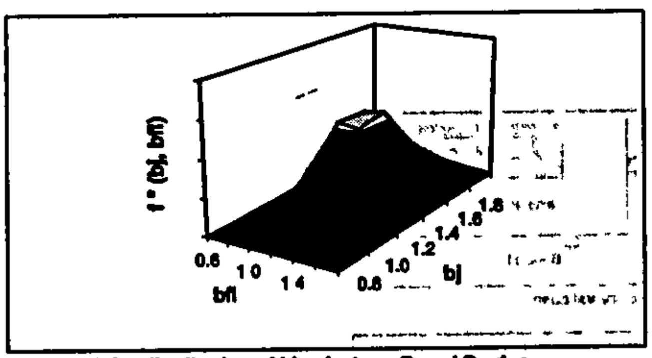


Fig. 11–Joint distribution of bias factors, B_j and B_{fl} due to an example platform undamaged during Andrew

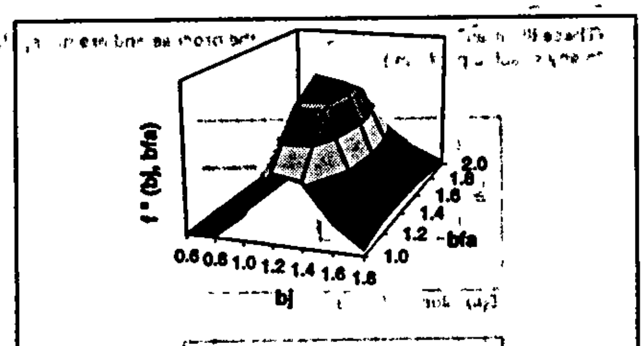


Fig. 12–Joint distribution of bias factors, B_j and B_{fa} due to an example platform undamaged during Andrew

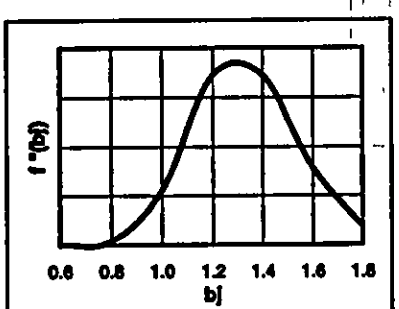


Fig. 13–Marginal posterior distribution of bias, B_j

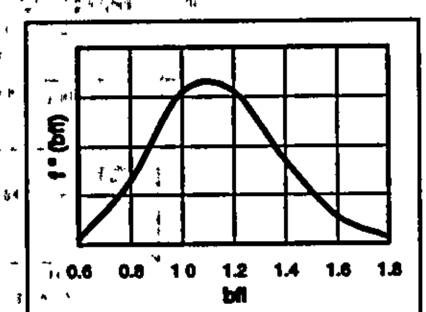


Fig. 14–Marginal posterior distribution of bias, B_{fl}

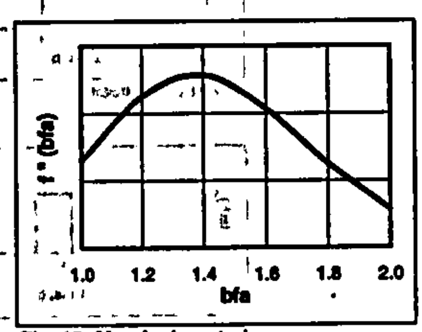


Fig. 15–Marginal posterior distribution of bias, B_{fa}